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Theoretical and experimental analysis of the vacuum pressure in a vacuum glazing after extreme thermal cycling

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Abstract

Details of theoretical and experimental studies of the change in vacuum pressure within a vacuum glazing (VG) after extreme thermal cycling are presented. The VG was fabricated at low temperature using an indium edge seal. It comprised two 4mm thick 0.4 m by 0.4 m low-emittance (low-e) glass panes separated by an array of stainless steel pillars with a diameter of 0.32 mm and a height of 0.2 mm. After thermal cycling in the temperature range -30°C to +50°C on one side of the sample, while maintaining 22°C on the other side, it was found that the glass to glass heat conductance of the sample had increased by 8.2%. The vacuum pressure within the evacuated gap was determined to have increased from 0.01 Pa to 0.15 Pa using the model of Corrucini. This is at the upper limit of the range where the effect of gas pressure on the thermal performance of VG can be ignored. The degradation of vacuum level determined was corroborated by the change in glass surface temperatures.

1. Introduction

Flat VG as shown in Fig. 1 consists of two plane glass sheets, separated by a narrow internal evacuated space, contiguously sealed together around their periphery. The space, maintained by an array of tiny support pillars, is evacuated to a pressure of <0.1 Pa, effectively eliminating both gaseous conduction and convection. The low-e coatings on the internal glass surfaces within the evacuated gap reduce the radiative heat transfer through the VG to a very low level. The VG concept was first patented by Zoller (1924) [1]. However, the first successful VG was not fabricated for many years, Robinson and Collins (1989) [2]. A solder glass powder laid along the periphery of the glass sheets melted to form the edge seal of the vacuum space when the entire glazing unit was heated to 450 °C. This high temperature method of fabricating VG prevents the use of tempered glass and some types of soft low emittance coatings thus preventing the high levels of performance predicted from being achieved. The University of Ulster has developed a methodology and system for the manufacture of low temperature sealed VG that can incorporate soft low-e coatings and tempered glass [3, 4]. A total heat transmission U-value of less than 1.0 $Wm^{-2}K^{-1}$ for a VG of small size (0.4 m by 0.4 m) has been experimentally determined [5] using a guarded hot box calorimeter (GHBC).

Outgassing and long-term vacuum stability of VG is an important issue [6, 7]. VG samples have been subjected to different temperatures for various periods of time. The levels of outgassing measured by using spinning rotor gauge when subject to static ageing conditions were

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experimentally measured and were in good agreement with the predictions [7]. In this paper VG manufactured at low temperature was subjected to extreme dynamic thermal cycling, and the effect on the vacuum pressure in the evacuated gap analysed using a model for heat conduction at low pressure [8]. The results were compared with the results of thermal testing using the GHBC [5].

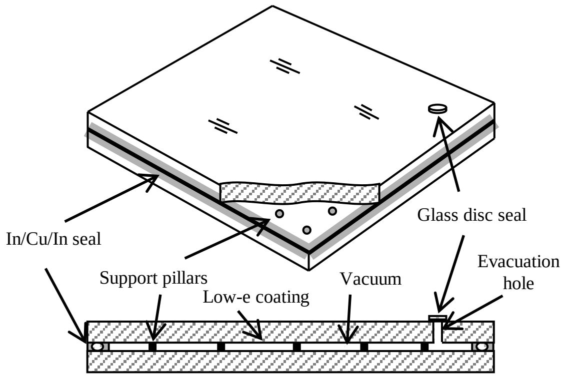

Fig. 1 Schematic diagram of a VG

2. Modelling approach

A three dimensional finite volume model (FVM) [9] and a two dimensional finite element model (FEM) [5] extensively validated experimentally in previous reported research [3, 10] were used to analyse heat transfer through a VG with the practical boundary conditions within the GHBC.

In the FVM model, the analytic model for heat flow through individual support pillars [6] was not employed since the pillar array was incorporated and modelled directly. The circular cross section of the pillar in the fabricated system was replaced by a square cross section pillar of equal area in the model. A graded mesh was used with a high density of nodes in and around the pillar to provide adequate representation of the heat transfer in this region. The residual gas pressure was assumed to be below that at which conduction was an issue. Simulations [11] predicted that for 0.4 m by 0.4 m VG rebated into a solid wood frame by 15.4 mm, the lateral heat transfer conducted $C_{lateral}$ through the edge seal increased the heat conductance of the central glazing area by 3.1%.

The FEM used the Galerkin approach with eight-node isoparametric elements. Further details of the FEM employed can be found in [9]. In the FEM model, the conductance of the central evacuated gap was determined by the analytic model of support pillars and radiative heat transfer between two glass panes. Using the same boundary conditions, the difference of heat conductance predicted by the FVM and the FEM is 1% [10].

In this FEM model, the influence of the residual gas on the heat conductance of the glazing can be modelled. When the measured temperature profiles do not match the predictions calculated using the FEM the effects of the residual gas should not be neglected [5]. Total glass to glass heat conductance of the central glazing area is determined by:

$$C_{centre} = C_{gas} + C_{radiation} + C_{pillars} + C_{lateral} \qquad (1)$$

$$= C_{gas} + 4\varepsilon_{effective}\sigma T^{3}_{average} + 2k_{glass}a/p^{2} + C_{lateral} \qquad (2)$$

Where σ is the Stefan Boltzmann constant (5.67×10^{-8} $Wm^{-2}K^{-4}$), $T_{average}$ is the average of the two glass temperatures T_1 and T_2, k_{glass} is the glass thermal conductivity, a is the pillar radius, p is the pillar separation and the effective emittance, $\varepsilon_{effective}$, is calculated from the surface emittance ε_1 and ε_2 by:

$$\frac{1}{\varepsilon_{effective}} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 \qquad (3)$$

Using the $C_{lateral}$ predicted by the FVM and the experimentally determined C_{centre}, the C_{gas} can be determined using equation 2. The effective heat conductance of the evacuated gap can be determined and temperature profiles calculated using the FEM.

3. Experimental determination of the heat conductance of a VG before and after thermal cycling

Fabricated VG measuring 0.4 m by 0.4 m was subjected to thermal cycling resulting in significant thermal stress gradients. The internal air temperature was maintained at 22°C and the external air temperature cycled between -30°C and 50°C. The VG heat conductance before and after thermal cycling was evaluated using the GHBC. The detailed description of the measurement method was reported in Fang et al., [5]. The temperatures of the glass surfaces, the air temperatures in the hot and cold boxes and glazing surface heat transfer coefficients during testing are listed in Table 1. The heat conductance through the VG before and after thermal cycling determined by the GHBC are presented in Table 2. Using equations 2 and 3, the heat conductance due to the residual gas levels were calculated and are listed in table 3.

Table 1. Experimental parameters in the guarded hot box calorimeter.

Thermal cycling	Air temp. hot & cold boxes (°C)		Hot & cold side glass temp. (°C)		Surface heat transfer coeff. ($Wm^{-2}K^{-1}$)	
	T_{a1}	T_{a2}	T_{g1}	T_{g2}	h_1	h_2
Before	27.4	7.9	23.7	9.6	5.65	12.78
After	26.4	4.7	20.2	7.8	3.84	7.84

Table 2. Predicted and experimentally determined heat conductance of the VG

	FVM predicted ($Wm^{-2}K^{-1}$)		Experimentally determined ($Wm^{-2}K^{-1}$)	
	$C_{glazing,\ p}$	$C_{centre,\ p}$	$C_{glazing,\ e}$	$C_{centre,\ e}$
Before	1.21	1.09	1.22±0.09	1.10±0.08
After	1.21	1.09	1.32±0.10	1.20±0.09

Table 3. Determination of residual gas conductance

	Predicted ($Wm^{-2}K^{-1}$)	Experimentally determined conductance ($Wm^{-2}K^{-1}$)			
	$C_{lateral,\ p}$	$C_{rad,\ e}$	C_{pillar}	$C_{centre,\ e}$	$C_{gas,\ e}$
Before	0.034	0.545	0.512	1.10	0.011
After	0.034	0.530	0.512	1.20	0.124

In the FEM, the heat conductance of the evacuated gap is determined by the residual gas and pillar array conductance and the effective radiative conductance. The calculated temperature profiles on the surface of the glass pane before and after thermal cycling are shown in figures 2 (a) and (b). It can be seen that the measured temperatures are in good agreement with the predictions calculated using the FEM. Before and after thermal cycling, the heat conductance due to residual gas increased from 0.011 to 0.124 $Wm^{-2}K^{-1}$. The heat conductance of the glazing increased by 8.2% from 1.22 to 1.32 $Wm^{-2}K^{-1}$.

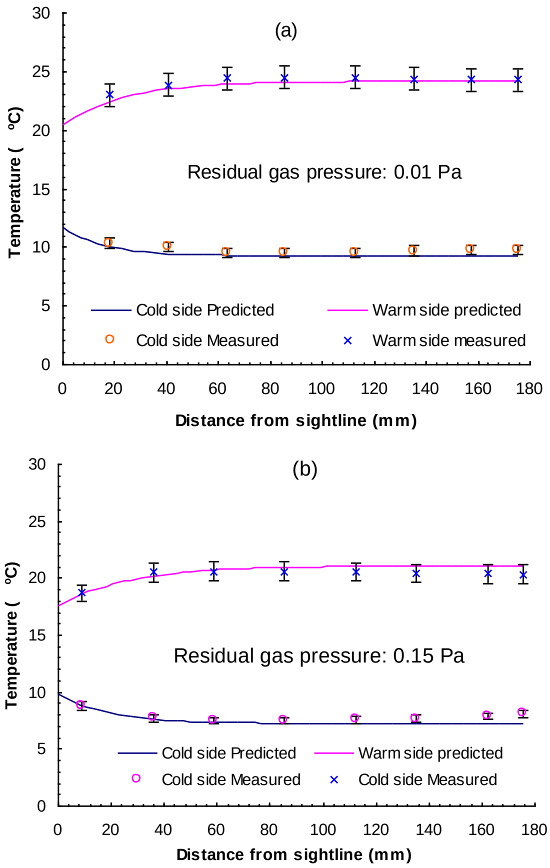

Fig. 2 Temperature profiles along the central line of glass surfaces, (a) before and (b) after thermal cycling.

4. Thermal conductance of residual gas within the VG

When gas pressure is reduced to a level at which the mean free path for molecule-molecule collisions is of the same order as the distance over which the heat is transported, a significant reduction of residual gas heat conductance takes place. The width of the evacuated gap in a VG is approximately 0.2 mm, this equates to a mean free path at a pressure of 30 Pa [6]. The gaseous conductance of the low pressure gas is proportional to gas pressure p [8]:

$$C_{molecular} = \alpha \frac{\gamma+1}{\gamma+1}\sqrt{\frac{R}{8\pi MT}}\,p \qquad (4)$$

Where γ is the specific heat ratio of the gas, M is the molar mass of the gas, T is the mean temperature of the two surfaces and R is the molar gas constant. The combined accommodation coefficient α is determined by the accommodation coefficients on the two surfaces, α_1 and α_2 by

$$\frac{1}{\alpha} = \frac{1}{\alpha_1} + \frac{1}{\alpha_2} - 1 \qquad (5)$$

Water vapour has been determined to be the main gas species in degraded samples of VG [6]. Water molecules interact strongly with the internal surfaces of the glazing. A combined accommodation coefficient of 0.9 was assumed. The gaseous conductance in the low pressure gap of VG is C_{gas} = 0.8P $Wm^{-2}K^{-1}$, where P is the gas pressure measured in Pascals. The pressures within the evacuated gap of the VG before and after thermal cycling were 0.01 Pa and 0.15 Pa respectively.

5. Conclusions

Fabricated VG measuring 0.4 m by 0.4 m, with a U-value of 1.0 $Wm^{-2}K^{-1}$ was subjected to extreme thermal cycling resulting in significant thermal stress gradients. An internal air temperature of 22°C was maintained while external air temperature was cycled between -30°C and 50°C. After thermal cycling it was found that the glass to glass heat conductance of the VG had increased by 8.2% from 1.22 $Wm^{-2}K^{-1}$ to 1.32 $Wm^{-2}K^{-1}$ while the centre of pane, glass to glass heat conductance increased by 9.1% from 1.10 $Wm^{-2}K^{-1}$ to 1.20 $Wm^{-2}K^{-1}$. Using the model for heat conduction in a vacuum [8], it was determined that the vacuum pressure within the evacuated gap increased from 0.01 Pa to 0.15 Pa. This is near the upper limit of the range developed by Collins and Simko [6], where the residual gas effect on the thermal performance of a VG can be ignored. The degradation of vacuum level determined by this model agreed well with the glass surface temperature difference predicted using a FEM.

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